ZF cPower – Hydrostatic-Mechanical Powersplit Transmission for Construction and Forest Machinery

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Abstract
Until recently, hydrostatic-mechanical power split CVT drivelines have not found a place in construction machinery. The majority of these vehicles still use hydrodynamic powershift transmissions, full-hydrostatic transmissions or mechanical direct-shift transmissions. Hydrostatic drive lines are widely used in construction machinery possessing lower engine power. The upper power range is dominated by hydrodynamic powershift transmissions. Decisions made by vehicle manufacturers about which driveline technology to be used, have been based mainly on reliability, durability, and cost. Fuel economy has also been a growing trend over the past years; however the additional cost of higher technologies must be compensated by the savings in fuel cost over a time period of 2-3 years. The transmission’s efficiency highly contributes to the vehicle’s fuel consumption.

ZF has thoroughly studied the possible concepts of hydrostatic-mechanical power split transmissions. The most important requirements of reliability, durability and efficiency were taken into consideration during the concept study. An examination the most typical working cycles showed that a construction machinery transmission needs to be fully power split in all ranges and obtain equal performance in both driving directions. It was also observed that up to 60% of productive time for construction and forestry equipment was spent at a speed below 12 km/h. For this speed range, achieving the highest possible efficiency is vital. The result of this research is the ZF cPower, which is an output-coupled, fully power split transmission.
1. Gear schematic and power flow

Figure 1 shows the gear schematic for a 2 range cPower transmission. The directional clutches (F, R) are located at the input of the cPower transmission. This allows equally high performance in both driving directions. The next element in the power path is the variator, which is comprised of a planetary gear set and a hydrostatic drive module.

The range clutches (C1 and C2) are located after the variator in the power path. Every range utilizes both mechanical and the hydrostatic power at the same time. The chosen concept for the cPower family of transmissions covers a wide range of engine power, from 90 kW up to 285 kW. The two range transmission can be used in combination with engines of up to 250 kW of power. At higher power levels, three ranges become necessary. The cPower is designed for a reduced rated engine speed of 1800 rpm.

A gear step at the transmission input allows the power take off (PTO1 and PTO2) for working hydraulic pumps to run at higher speeds than engine speed. This allows OEMs to keep the same working hydraulic pumps, which they use today while operating the cPower at lower engine speeds.

Figure 1: Gear schematic for 2 range cPower
The planetary system is comprised of four elements. There is a planetary carrier with stepped planetary gears. The first sun gear is connected with the first hydrostatic unit. The ring gear is connected by a spur gear to the shaft of the second hydrostatic unit. The second sun gear is connected by a spur gear to the loose gear of the second range clutch. This planetary system is required for synchronized range changes. For synchronized range changes, the ratios in planetary gear set, and in the spur gear set at the range clutches, need to be selected to prevent differential speed in the open clutch at the range change point. This allows the clutch to close without transferring power and being felt by the driver. There is also no reduction of tractive effort when changing ranges.

As soon as the output begins to turn, the cPower allows for a full power split. A portion of the input power will pass through the transmission mechanically. The other portion is transferred through the two hydrostatic units. The power distribution varies according to the ratio of the transmission. The first range displays a typical output power split behaviour. In second range, cPower uses a compound power split mode. Figure 2 explains the hydrostatic/mechanical power distribution to the transmission output over ground speed at rated engine speed.

![Power distribution](image)

**Figure 2**: Power distribution though the transmission

The maximum portion of hydrostatic power used in the first range is 60 %. As soon as the transmission output begins to turn, the mechanical portion of power begins to increase. In the middle of the first range, the power split of hydrostatic / mechanical power is 50 % / 50 %. At the end of the first range, the hydrostatic power flow decreases to zero and the mechanic power portion reaches nearly 100 %.

In second range, due to the compound power split mode, the maximum hydrostatic portion of power flow reaches only 34 %, which allows a mechanical power portion of at least 66 %. At the end of the second range, the hydrostatic power flow is reduced to zero and the mechanical power portion reaches 100 %.
The high portion of mechanical power flow through the transmission and the highly efficient hydrostatic units lead to a very high total efficiency of the transmission. There is nothing more efficient, than mechanical power flow through a transmission!

2. Hydrostatic module and control

2.1. Design and function

The hydrostatic module shown in figure 3 includes two wide angle, bent axis, axial piston kits within a dual yoke. In the dual yoke, both kits are oriented at an angle of 45° to each other. If one kit is at 0°, or zero displacement, the other kit is at 45°, or maximum displacement. The dual yoke requires one control element for the entire hydrostatic module, a further advantage of simplicity.

![Figure 3: Hydrostatic module](image)

The design of the hydrostatic kits includes lubrication through the center of the shafts. This allows the kits to be operated in the air, eliminating any splashing losses. Common hydrostatic units operate in housings filled with oil, causing high splashing losses.

All valves which are typical for a hydrostatic module are located in the dual yoke. The two oil channels for oil flow between the kits are casted into the dual yoke housing. These channels are optimized in regards to pressure loss. The control lever is part of the dual yoke housing, and determines the swash angle of the hydrostatic module. The dual yoke housing pivots within two brackets mounted to the base plate. Charge oil, and high pressure oil for hydrostatic module control, are both fed through the brackets. The hydrostatic kit bearings are located in the base plate along with the control piston, which sits between two pressure chambers and is connected to the control lever.
The complete hydrostatic module is mounted by isolators (rubber-metal) to the transmission. The two shafts of the kits are connected with profile shafts to the transmission shafts. These shafts allow for relative movement of the hydrostatic unit to the transmission.

![Hydraulic schematic of hydrostatic module](image)

**Figure 4:** Hydraulic schematic of hydrostatic module

A very important element in the base plate is the control valve for the hydrostatic module. The control valve includes a proportional magnet, a position control valve, a spring and a feedback piston. This control valve is a force balance system. The proportional magnet force is always in a balance with the force of spring between position control valve and feedback piston.

### 2.2. Compact design

The hydrostatic module is a very compact design due to the wide angle, bent axis axial piston kits, the dual yoke and the selected high pressure control of the yoke housing. The axial distance of the two hydrostatic kits is mainly defined by the outer diameter of the taper roller bearing and the thickness of the control lever between the two kits.

### 2.3. High pressure control for hydrostatic module

The focus for controlling the hydrostatic module was high dynamics. In wheel loader applications, the required dynamics while digging into a pile is very high. If the
deceleration of the machine were to be faster, than the ratio change in the power split transmission, the engine would be stalled. The requirement to control a full stroke (45°) in a time of 250 ms has led to the decision to use a high pressure control. High pressure control allows for low oil flow.

With the selected dimensions, a maximum oil flow of only 7.8 l/min (based on 90 bar available pressure difference) through the control system was required. For a low pressure control system with equal forces to control the hydrostatic module, a flow of 46.8 l/min (based on 15 bar available pressure difference) would have been necessary.

In a high pressure control system, it is also necessary to use a control valve with low leakage. Leakage measurements with this control system had shown a maximum leakage of only 400 ml/min @ 300 bar.

The above mentioned oil flow for the control of the hydrostatic module is supplied by the transmission pump. The transmission pump must deliver the oil flow for clutch control at a system pressure of 20 bar. Additionally, charge flow for the hydrostatic circuit, hydrostatic module control and lubrication oil flow for the transmission must be provided by this transmission pump. The required oil flow needs to be available at an engine speed of 1000 rpm.

The lower pump oil flow requirement with a high pressure control for the hydrostatic module reduces the permanent power consumption. This reduces power loss by 1.3 kW at an engine speed of 1000 rpm. At the rated engine speed of 1800 rpm, power loss is further reduced by 2.3 kW

3. Efficiency

Figure 5 below shows the efficiency curves for a two-range cPower transmission in comparison to a 4-speed torque converter power shift transmission. Because cPower is fully power split in the 1st and 2nd range, the efficiency remains stable through the entire vehicle speed range. The hydrostatic module transmits a higher percentage of power at lower vehicle speeds. At these low speeds, where high torque is needed, the power losses of cPower are much lower than a torque converter transmission. This can be viewed in figure 6. At higher speeds, power is transmitted mechanically, allowing the cPower efficiency to remain high while a hydrostatic transmission would lose efficiency rapidly. The first range of cPower covers vehicle speeds of up to 10 km/h allowing highest possible efficiency during productive work. The high and constant efficiency allows more flexibility for OEMs to optimize their power packaging and working hydraulics according to their own operation strategies.
4. Fuel consumption reduction

There have been numerous occasions of testing by OEMs and also end user testimonials which underline the fuel consumption advantages cPower offers. One OEM compared its series production vehicle using a hydrostatic transmission with the same vehicle using a cPower transmission. As expected, the cPower transmission achieved up to 28% fuel savings in long loading cycles. Even in the short load cycles, or truck loading, the cPower showed a fuel consumption reduction of 8% compared to the current hydrostatic drive line.
A separate customer compared its series production vehicle using a 5-speed hydrodynamic transmission with a torque converter lock-up clutch to the same vehicle using a cPower transmission. This OEM showed a productivity increase (tons per liter of fuel) using cPower of up to 29% in the truck loading cycle, 23.8% in the long loading cycle and 12.5% in transportation mode.

Testimonials from end users confirm these results. A paper mill operator reported a daily savings of up to 200 liters of fuel using the cPower compared to a fully hydrostatic drive line of the same size with no loss in productivity. Per day, 700 liter were consumed by the former vehicle, and with cPower, only 500 liters was consumed. Another operator loading coal reported that the current fully hydrostatic vehicle being used consumed up to 27 liters of fuel per hour. The same vehicle using cPower consumed only 19 liters per hour. That is a fuel consumption savings of 30%.

5. Field test
An extensive field test was performed by both pilot customers, and is required before any new application or customer. The field test is used as a final system validation before series production begins. Testing vehicles in real job applications provides opportunity to find any and all problems with software and hardware for the entire drive train. 

CP190-230 field testing has accumulated almost 24,000 hours with several different OEMs. The field tests include applications in wheel loaders and forestry machines in several different regions and operating environments. Some of the operating environments include stone quarries, recycling centers, forests in the south eastern United States, Canada and Finland. CP290 field testing has accumulated over 26,000 hours with different OEMs in the wheel loader application. CP310 field testing has accumulated over 32,000 hours of testing in the wheel loader application. Combined, cPower field testing has achieved over 82,000 hours. 

cPower started series production in 2014 with the skidder application. Since then, over 420 skidders have been built. These machines have already accumulated over 100,000 hours of operating time.